Improved simulation of extreme precipitation in a high-resolution atmosphere model

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[1] Climate models often underestimate the magnitude of extreme precipitation. We compare the performance of a high-resolution ($\sim 0.25°$) time-slice atmospheric simulation (1979–2005) of the Community Earth System Model 1.0 in representing daily extreme precipitation events against those of the same model at lower resolutions ($\sim 1°$ and $2°$). We find significant increases in the simulated levels of daily extreme precipitation over Europe, the United States, and Australia. In many cases the increase in high percentiles (> 95th) of daily precipitation leads to better agreement with observational data sets. For lower percentiles, we find that increasing resolution does not significantly increase values of simulated precipitation. We argue that the reduced biases mainly result from the higher resolution models resolving more key physical processes controlling heavy precipitation. We conclude that while high resolution is vital for accurately simulating extreme precipitation, considerable biases remain at the highest available model resolutions. **Citation:** Kopparla, P., E. M. Fischer, C. Hannay, and R. Knutti (2013), Improved simulation of extreme precipitation in a high-resolution atmosphere model, *Geophys. Res. Lett.*, *40*, 5803–5808, doi:10.1002/2013GL057866.

1. Introduction

[2] In a changing climate, the water content of the atmosphere is expected to increase by about 7% for each degree Celsius of temperature rise according to the Clausius-Clapeyron equation, leading to changes in precipitation patterns and intensities [*Boer*, 1993; *Pall et al.*, 2007; *Allan and Soden*, 2008; *Kendon et al.*, 2010]. While mean precipitation is constrained by the global energy budget, precipitation extremes in the midlatitudes are constrained by the water content of the atmosphere and thus are expected to increase in intensity more strongly than the mean [*Allen and Ingram*, 2002; *Lenderink and van Meijgaard*, 2008]. But these changes in extreme precipitation also depend on changes in several other factors such as the temperature when precipitation occurs, the moist adiabatic lapse rate and vertical velocity [*O'Gorman and Schneider*, 2009a] which operate on small scales and are often not fully resolved on current model grids. On a large scale, light and moderate precipitation frequencies are expected to decrease almost everywhere, while extreme precipitation becomes more common [*Trenberth et al.*, 2003; *Gutowski Jr. et al.*, 2007; *Sun et al.*, 2007]. Current global climate models, such as those being used in the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report, agree reasonably well on the projected changes in future precipitation [*Tebaldi et al.*, 2006, 2011; *Knutti and Sedláček*, 2012] but have deficiencies in capturing the intensity of extreme precipitation events [*Kharin et al.*, 2007; *Stephens et al.*, 2010; *Sillmann et al.*, 2013], and this reduces confidence in their projections. Specifically, *Sillmann et al.* [2013] find that the Coupled Model Intercomparison Project (CMIP) Phases 3 and 5 models underestimated extreme precipitation across several measures, including daily precipitation intensity and maximum 5 day total precipitation intensity. It has been suggested that physical processes governing extreme precipitation in these models are not well represented; in particular, subgrid processes and convective parametrization have been persistently suspected of causing this inadequacy [*Shiu et al.*, 2012; *Wilcox and Donner*, 2007].

[3] The horizontal grid resolution of the model has long been considered an important factor in simulating extreme precipitation [*Pope and Stratton*, 2002; *Roeckner et al.*, 2006; *Salathé et al.*, 2008; *Shaffrey et al.*, 2009, and references therein]. High-resolution models can begin to explicitly resolve convective flows, apart from representing orography appropriately. Also, *Iorio et al.* [2004] have shown that smoothing, which results from a single model grid box representing a large area, reduces extreme precipitation values disproportionately. Thus, a high-resolution simulation with its smaller grid boxes is expected to better preserve natural spatial variability, which is very important for simulating precipitation. Naturally, there have been efforts by nearly every modeling group to run their models at the highest possible resolution affordable with the available computing power. However, increasing grid resolution often requires a "retuning" of parameterizations (i.e., a readjustment of model parameters to reduce biases) to show improvement in model performance. This is because model parameterizations are typically resolution dependent [*Duffy et al.*, 2003]. Also, changes which bring improvements in some output fields cause deterioration in others [*Pope and Stratton*, 2002]. Thus, it becomes necessary to examine changes closely whenever the resolution of a model is modified.

[4] Here we investigate the differences in simulated extreme precipitation over Europe, United States, and Australia using an atmospheric general circulation model (AGCM) at three different grid resolutions. The idea is to evaluate improvements caused by changes in grid resolution, with as few changes as possible in model parameters. This

Additional supporting information may be found in the online version of this article.

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study takes the work of *Wehner et al.* [2010], who showed improvements in extreme precipitation with increasing grid resolution in an AGCM (0.5° × 0.625°) over the United States, further to higher resolutions and other continents where highly resolved observational data sets are available.

2. Data and Methods

[5] The model data consist of simulations using the Community Atmosphere Model version 4 (CAM4) [*Neale et al.*, 2013] which is the atmospheric component of the Community Earth System Model (CESM), version 1.0 [*Hurrell et al.*, 2013] developed at the National Center for Atmospheric Research (NCAR). This model is a subset of the Community Earth System Model (CESM) 1.0 code base and will be referred to as CESM in the following discussion. We analyze results from CESM each at horizontal resolutions of 0.23° × 0.31° and 1.88° × 2.5°, and six members at 0.94° × 1.25°. For the sake of brevity, these simulations will be referred to as the 0.25°, 2°, and 1° simulations, respectively. Minimal retuning is done at 0.25° to reduce the cloud radiative forcing bias in middle and high latitudes. Each of the 1° simulations has slightly perturbed atmospheric initial conditions, and the differences between these simulations are a measure of model variability in the atmosphere. Over Europe, evaluations were carried out against the ENSEMBLES gridded observational data set (EOBS), version 6.0 with a grid resolution of 0.25° [*Haylock et al.*, 2008]. For the contiguous United States, the NOAA Climate Prediction Center (CPC) [*Higgins et al.*, 2000, CPC U.S. Unified Precipitation data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/], gridded observational data set was used, also at a resolution of 0.25°. Over Australia, daily precipitation data from the Australian Water Availability Project (AWAP) [*Jones et al.*, 2009] regridded to a resolution of 0.5° was used for evaluation.

[6] To compare data on different grids, the data at higher resolution were regridded to match the coarser grid using two separate methods, bilinear interpolation and uniform areal averaging. Areal averaging is conservative, but bilinear interpolation is not, which leads to some interesting effects. With bilinear interpolation, regridding has very little "smoothing" effect—the value of precipitation extremes changed by less than 5% after interpolation. The reasons for this are discussed in the final section.

3. Results and Discussion

[7] Figure 1 shows the biases in CESM at 0.25°, 1°, and 2° over the U.S., Europe, and Australia against the respective regional data sets for the 99th percentile of extreme daily precipitation. The observational data sets were area averaged to match the model grids in all figures shown here. Increasing grid resolution consistently produces higher values of simulated extreme precipitation over most regions under consideration. In many cases, this leads to an improved representation as current models are unable to produce sufficiently heavy precipitation. The bias is the difference between the 99th percentile precipitation value in the model and observations for each grid box. The root-mean-square error value for the biases across all the grid boxes is noted in each panel and serves to provide a cumulative measure of the bias. Panels with smaller root-mean-square error (RMSE) values imply better agreement with the observational data sets. Clearly, the area-aggregated bias decreases with increasing resolution over Europe and the U.S. In the U.S., we note that there is substantially reduced underestimation bias in the Midwest and but also an enhanced overestimation over the Rockies and the Sierra Nevada that is not seen at coarse resolution. Also, the regions of overestimated extreme precipitation at high-resolution match regions of high elevation very closely. This likely results from steeper altitude gradients at high resolution, which enhance orographic precipitation. *Wehner et al.* [2010], using an older version of the GCM used here at resolutions of around 0.5°, showed that increasing grid resolution improves the model's ability to simulate extreme precipitation over the U.S. Our findings confirm these results, while extending them to a resolution of 0.25° and to two other continents. In Europe, the high-resolution model slightly overestimates extreme precipitation over parts of eastern Europe and Turkey and underestimates it over western Europe. Note that all mountainous regions tend to have precipitation biases. But there is significant improvement at high resolution, most noticeably over the Alps and Scandinavian mountains. In contrast to the U.S. and Europe, the enhanced extreme precipitation at high resolution over Australia leads to biases in the opposite direction due to overestimation already present in the coarse resolution model. *Perkins et al.* [2007] showed that the climate models used in the IPCC Fourth Assessment Report without exception underestimated the magnitude of extreme precipitation events over Australia. The present 1° simulations seem to have overcome this limitation, and in the case of 0.25°, they even overestimate the precipitation in Northern Australia. This overestimation of the area affected by strong monsoon precipitation strongly contributes to the continental RMSE. The correct representation of the Australian monsoon is challenging for models and is affected by biases which do not necessarily change with resolution. *King et al.* [2013] demonstrate that observational data over Australia generally underestimate precipitation extremes when compared to meteorological station data; however, stations in southern Australia come closest to reproducing observed variability. They also recommend not relying on AWAP data from areas with low station density, such as most of central and north Australia, since it tends to show spurious trends. Seasonal extreme precipitation trends for summer and winter (in the supporting information Figures S1 and S3) mostly follow the annual trends. However, in winter, there is no improvement over Europe, but a significant reduction in bias over Australia at high resolution.

[8] Figure 2 shows that on days with extreme precipitation, the fraction of resolved precipitation increases with increasing resolution over nearly all areas. We use the term "large-scale precipitation" to denote precipitation resulting from resolved flows following notation from the model output. Note that this includes precipitation from large to middle size convective flows, whose extent is larger than that of the model grid (about 25 kms at the equator at the highest resolution). The typical size of parameterized convective system at each resolution can be guessed from the size of the convective (red/white) features in Figure 2. Over Europe, Australia, and the U.S., regions where extreme precipitation is underestimated consistently have a high fraction of parameterized convective precipitation at all resolutions.

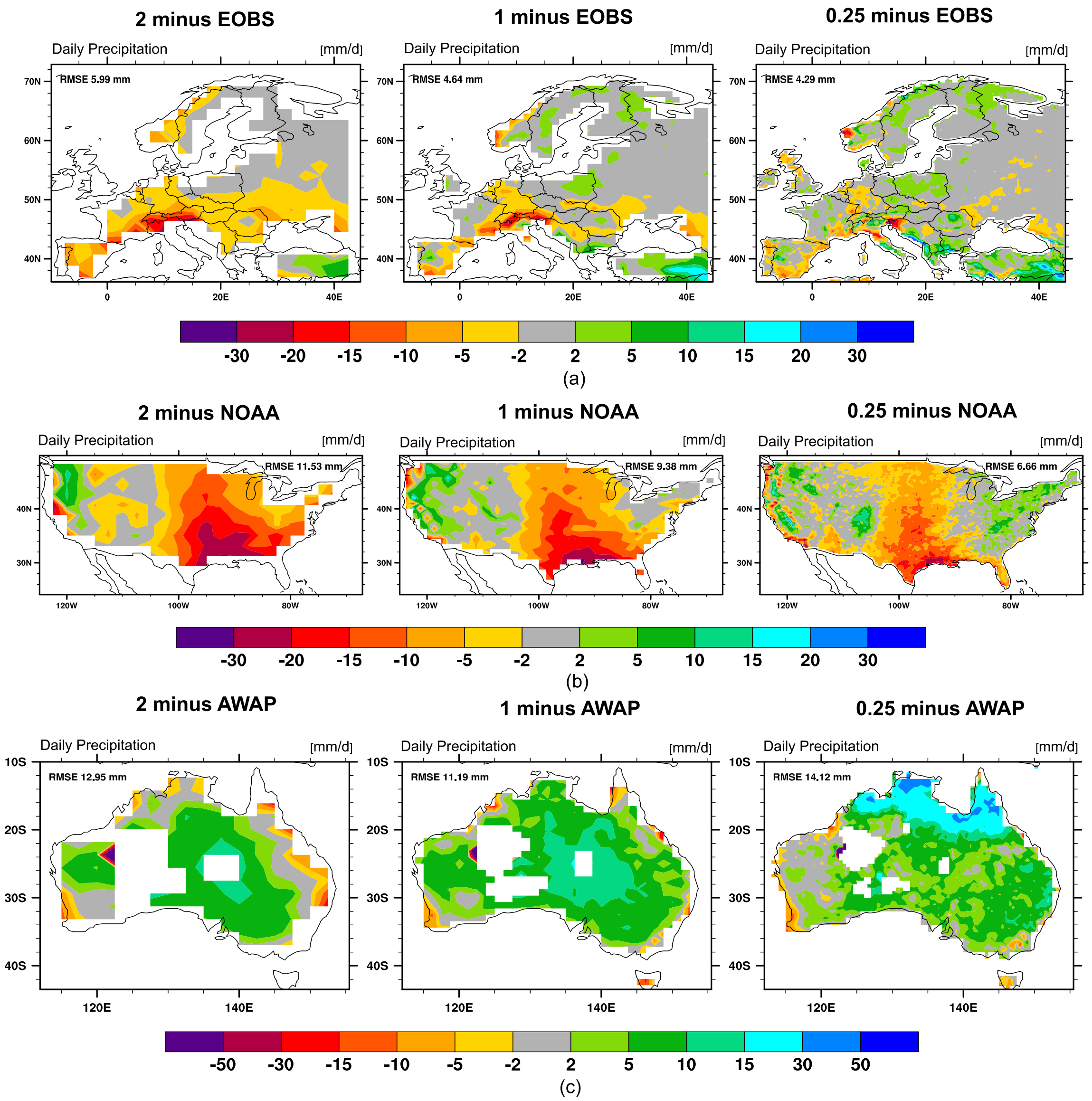

Figure 1. Biases in CESM over (a) Europe, (b) contiguous U.S., and (c) Australia measured against EOBS, NOAA CPC, and AWAP observational data sets, respectively, for the 99th percentile extreme precipitation (daily aggregated values), period 1979–2005. Title indicates the grid original resolution of CESM, the 0.25 run is interpolated to 0.5 × 0.5 for comparison with the AWAP data. RMSE is the root-mean-square value of the bias across all grid boxes.

One exception is the western tip of Scandinavia, where precipitation is underestimated, despite a significant fraction of large-scale precipitation, potentially due to too smooth topography. Notice that regions where fraction of resolved precipitation exceeds 60% cease to underestimate extreme precipitation compared to observations, as seen in Figure 1; however, there is overestimation over some such regions. Our results are consistent with (Bacmeister et al., Exploratory high-resolution climate simulations using the Community Atmosphere Model (CAM), *Journal of Climate*, unpublished data, 2013) who show that, while the precipitation produced by the deep and shallow convection scheme is rather insensitive to resolution, the precipitation maxima produced by the models' large-scale condensation routines (large-scale precipitation) strongly increase with higher resolution. In summer, we expect that deep convection causes a significant percentage of extreme precipitation over continental regions, and in winter, extreme precipitation results mostly from large-scale flows over the extra-tropics. We see that this behavior is well captured by the model at all resolutions (Figures S2 and S4). Apart from this, more realistic representation of topography, land surface heterogeneity and coast lines may also have been beneficial at high resolution. Since subgrid-scale parameterizations are resolution dependent, some parameters vary with resolution. While these adjustments have been limited to a minimum, it is not possible here to exclude an effect of these changes to the extreme precipitation.

[9] Similar to how RMSE values were calculated for the 99th percentile in Figure 1, we calculate RMSE values at other percentiles. Figure 3 shows the dependence of the RMSEs on increasing percentile values over different regions. Over all regions, a change in resolution has less of an effect on the biases for light to moderately heavy rainfall (up to 90th percentile) for which the contribution of large-scale systems is expected to be more important. At

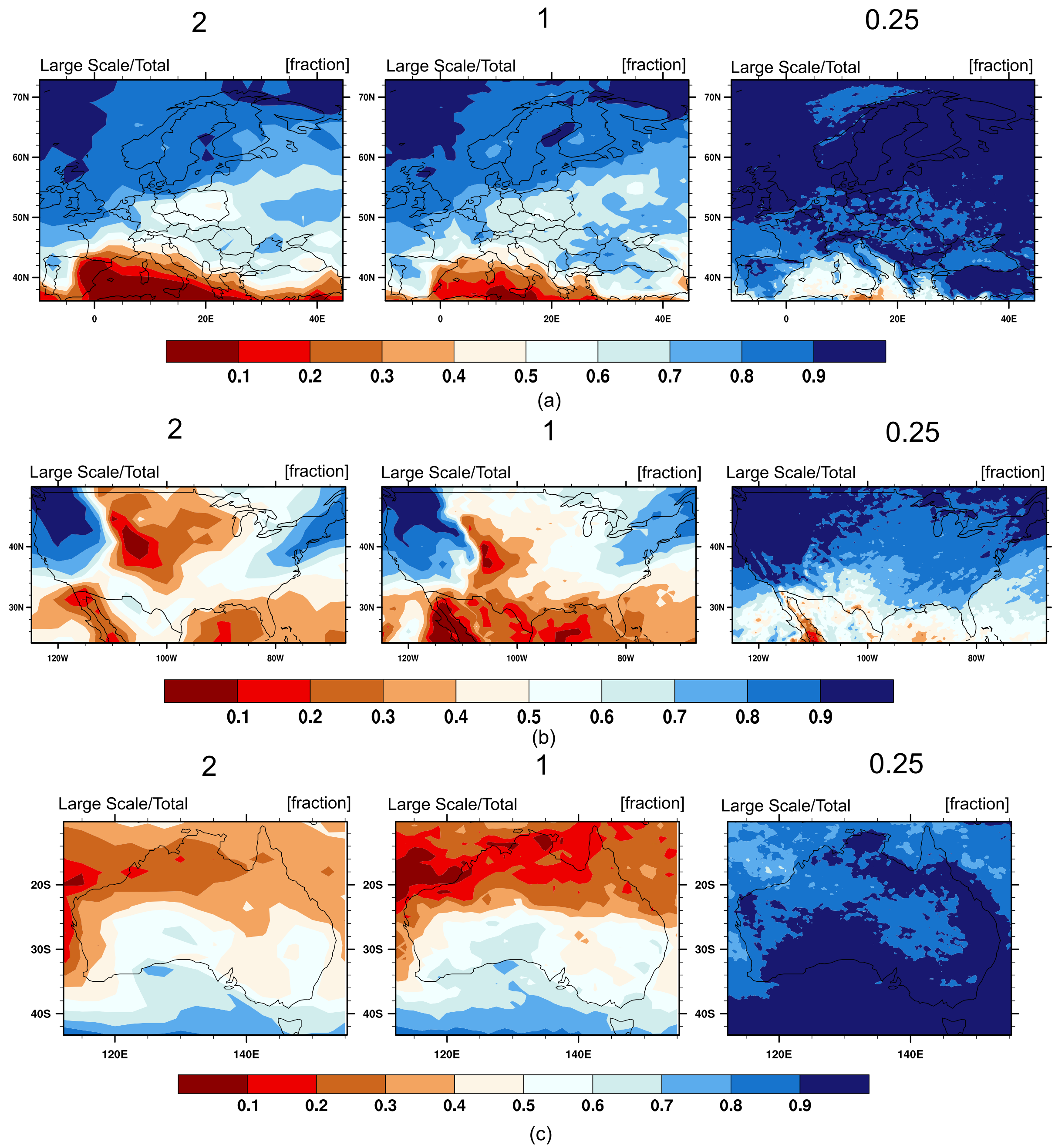

Figure 2. Fraction of large-scale (resolved) precipitation in CESM over (a) Europe, (b) contiguous U.S., and (c) Australia over all days exceeding the 99th percentile extreme precipitation (daily aggregated values), period 1979–2005.

higher percentiles, there is significant spread among the six 1° simulations, indicating that despite prescribed sea surface temperatures, model variability is a significant factor. Over the U.S., it is clear that the increase in simulated extreme precipitation values directly translates to lower biases. Over Europe, there is some improvement at high resolution, but it is not significant beyond the 99th percentile. Over Australia, biases are smallest at intermediate resolution—increasing resolution continuously increases the values of simulated extreme precipitation (Figure 1); while the 2° simulation tends to underestimate extreme precipitation values, the 0.25° run overestimates them and the 1° simulation shows the best agreement with observations. Also, we see that model variability, as seen by the spread of the six 1° simulations, is comparable to the interresolution differences at higher percentiles. Since we expect high-resolution models to preserve natural variability in the absence of smoothing effects, we can only speculate how large the spread will be among a set of 0.25° simulations.

[10] Data from the high-resolution model simulation were spatially aggregated using both bilinear interpolation and uniformly weighted areal averaging to 1° and 2° and then evaluated against observational data sets to observe the effects of smoothing. We found that the 0.25° simulation still performed better than both the coarse resolution simulations even with aggregation. With areal averaging, model biases decreased as a larger area was aggregated. This finding is consistent with that of *Räisänen* [2001] and *Masson*

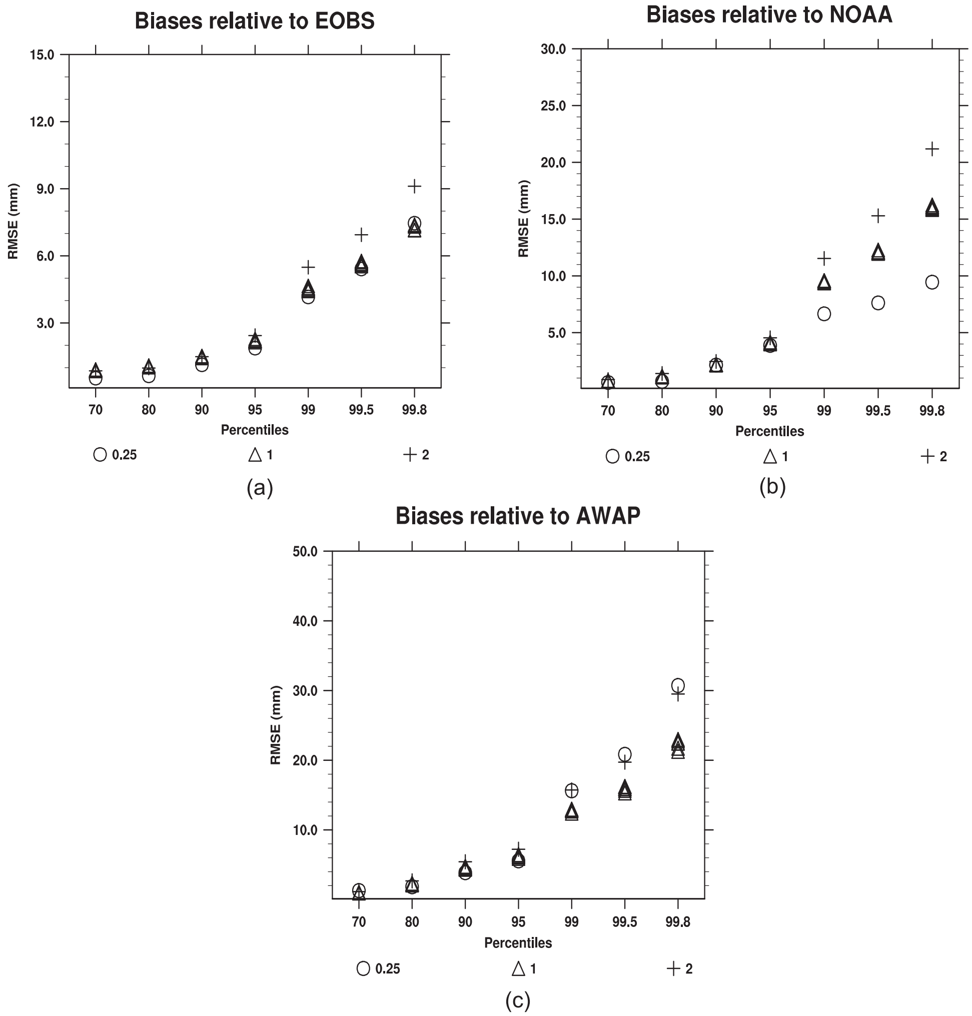

Figure 3. Root-mean-square errors for biases in CESM over (a) Europe, (b) contiguous U.S., and (c) Australia, measured against EOBS NOAA CPC and AWAP, respectively at different percentiles for precipitation (daily aggregated values), period 1979–2005.

and Knutti [2011], who argue that spatial aggregation leads to smaller errors as models become more similar at larger spatial scales. However, using interpolation, biases decreased when grid size was reduced to 1°, but increased when resolution was further reduced to 2°. The interpolation of precipitation data to the coarse grids also did not cause a significant "smoothing" effect. The lack of smoothing can be attributed to the manner in which interpolation was used. Consider for example that we are interpolating precipitation data from a 0.25° to a 2° grid. To calculate the precipitation value at a grid point on the new, coarse grid, we interpolate the precipitation values at single grid points on the old grid closest to this new point to the north, south, east, and west. Thus, this point will contain interpolated data from only four points of the 0.25° grid, instead of the 16 points that we get with areal averaging, greatly reducing the smoothing effect. For transforming data between grids of different resolution, we find that it is preferable to use areal averaging instead of interpolation, if spatial aggregation is the intended result. These considerations are valid for other nearest neighbor interpolation schemes, such as splines.

[11] Precipitation data sets suffer from strong biases particularly during extreme precipitation, due to large spatial and temporal variability. Using slightly lower resolution observations ($\sim 0.5°$) over Australia, we find that the increases in simulated extreme precipitation values actually result in higher biases (Figure 3c). While we remain mindful that particularly for extreme precipitation, the gridded observational data sets involve substantial uncertainties due to the gridding methodologies or deficiencies in the in situ measurements, we are confident that our findings are reasonably robust, since we are using the most up-to-date data sources for two continents and one large country. Our findings emphasize that it is vital to perform model evaluation over several continents to get a comprehensive picture.

4. Conclusions

[12] We find that enhancing model resolution has the potential to improve the representation of extreme precipitation. Our analysis shows that increasing model resolution leads to a greater fraction of resolved precipitation, which contributes to higher maxima and thus less pronounced underestimation of extreme precipitation over Europe and the U.S. and an overestimation over Australia. Thus, increasing resolution is critical at least for simulating extreme

precipitation, but it is not sufficient by itself. It is promising that the representation of extreme precipitation at 0.25° is better than coarse resolution simulations over substantial areas since the 1° model has been extensively evaluated during model development whereas 0.25° version has not. We may expect to see radical improvements in performance when convection is well resolved at scales of 1 km or less. But the realistic representation of many other factors including, but not limited to, vertical wind velocity and lapse rate [*O'Gorman and Schneider*, 2009a, 2009b], the diurnal cycle and boundary layer processes [*Schlemmer et al.*, 2011, 2012] and land surface interactions [*Seneviratne et al.*, 2010] will also be necessary.

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